LESSONS LEARNED FROM SELECTING AND TESTING SPACEFLIGHT POTENTIOMETERS

'1. Iskenderian*

ABSTRACT

A solar' array drive (SAD) was designed for operation on the 1 OPE X/POSEIDON spacecraft that was launched in August of 1 992. 1 he experience gained in selecting, specifying, testing to failure, and redesigning its position sensor produced valuable lessons for future component selection anti qualification. Issues of spaceflight heritage, cost/benefit/risk assessment, and component specification are addressed. It was found that costly schedule and budget overruns may have been avoided if the capability of the candidate sensors to meet requirements had been more critically examined prior to freezing the design. 1 he use of engineering models anti early qualification tests is also recommended.

IN-I RODUCTION

Uncommon rotational axis pointing accuracy, for a SAD, is required due to the precision orbit determination ([1 0[]) requirements on the '1 OP'E X/P'OSEIDON spacecraft. '1 his information is vital to the primary mission of the spacecraft, which is to survey the variation in ocean elevation to an accuracy of a few centimeters over the period of at least three years. '1 Of 'F X/P'OSEIDON uses a single, very large scalar array that acts as a sail in the solar wind. The solar pressure! and aerodynamic forms acting on the array cause much of the total non-gravitational forces which must be accounted for in the POD process; if orientation of the array with respect to the satellite body is in error, the solar pressure anti aerodynamic form models will be in error. '1 ho total error allocation from POD for the pitch, or rotational axis of the SAD, is 5.6 mrad (0.3? °),1 sigma, for all error sources, including thermally induced anti structural misalignm ents. "1 hat amount of error corresponds to a worst-case altitude error of about 1 cm. A 3-sigma accuracy requirement of 0.1 $^0/_0$ absolute linearity was assigned to the position sensor in the process of allocating the pitch axis error to all sources of uncertainty.

Besides high accuracy, continuous rotation in either direction is necessary, with no interruption of signal, Operating rate in flight could range: from zero to 110 mrad (6.3°) per minute, but could go much higher in ground test. Life, in terms of total number of revolutions, was not a major design challenge for any of the options we studied. An electronic moans of switching between potentiometer (pot) elements to maintain continuous function over 360° was proposed, which removed the reliability concern of mechanical switchover.

* Jet Propulsion Laboratory/California Institute of 1 echnology, Pasadena, Ca

Pots, optical encoders, resolvers, and induction-based technologies were considered. However, pressure to minimize cost led to selection of a pot, with its low component and electronics costs. When one pot vendor was found who could meet the requirements and demonstrate spaceflight experience, a pot-based scheme was chosen for its substantially lower estimated total cost. JPL contracted with Schaeffer Magnetics, Inc. to design and produce the SAD assembly, and to integrate the vendor-supplied pots with the SAD upon final assembly.

Problems with electrical noise and poor mechanical integrity of the pots began to show up as soon as environmental tests began. After four design cycles and three rounds of failure analysis, all problems except for electrical noise were completely corrected. Although the noise! was reduced to a large extent, development problems halfway through the effort prompted the project management to seek risk reduction by asking for an additional means of position feedback. Thus an electronic motor-stop counting circuit, named the SAD Incremental Counting Mode (SICM), was designed and built concurrently with the pot rework efforts. The final configuration of the SAD mechanism is shown in figure 1. Figure 2 shows the general layout of the pot mounting and surrounding structure.

As a result of the failures and efforts to eliminate them, the SAD delivery was delayed by one year, anti the cost overran the maximum estimate by approximately 5 00/0.

The spacecraft was launched successfully on August 10, 1992. Since then, the pot position signal has been nominally in agreement with the position calculated from the step counting electronics. While the SICM is used most often in the SAD's position control loop for reasons of signal processing convenience, the pot has not displayed any noise in the spacecraft's telemetry.

REQUIREMENTS AND TRADE STUDY

Early in the design process, a study team was chartered to perform a cost-vs-performance trade and determine the best mans of position sensing. The following overview describes the main issues which the study team considered; Table 1 summarizes the most significant requirements in that study.

Table 1
Position Sensor Requirements

Position Knowledge Accuracy, 3 Sigma	7.22 mrad (±0.4140), ±0.1 15°/0 absolute linearity
Mechanical Range) of Motion	±360° continuous rotation
Electrical Range	±360° Continuous rotation arid signal output

Signal Output	12 bit digital
Reliability	Electrically redundant
Life	30,000 revolutions
Environmental:	
Thermal	-30° C to +85° C design limits
Dynamic	19.6 g rms, 20 -- 2000 Hz random 5 g peak, 11---100 Hz sine
Radiation	100 krad

An industry survey identified the candidate sensor options. After considering several vendors, the characteristics of the best representative of each type were compared. Table 2 summarizes these findings.

Table 2
Position Sensor Trade Options

Characteristic	Pot	Optical Encoder	Resolver	Inductively Coupled
Accuracy, 3 sigma	±6.8 mrad	±1.5 rnrad (12-bit A/D) or better	±1.5 mrad (12-bit A/D) or better	±1.5 mrad (IZ-bit A/D) or better
1988 Estimated Cost (electronics & sensor), normalized to pot	1.0	8.7	5.8	6.7
Reliability concerns	Electrical noise in vacuum, wiper lubrication	High parts count	Requires qual program for discrete 16-bit R/D, also slip rings or rotary transformer	High parts count
Other concerns			Mass	Mass and power

We initially chose a resolver as the solution that would meet the accuracy requirement with acceptable cost and power. We selected three units as representative, each advertised with 1.2 mrad or better accuracy.

As the project's requirements and scope matured, however, the relatively high cost and mass of the resolver-based system caused much attention to be focused on the potentiometer option. At just under 1 kg per redundant unit, resolvers made the 0.24 kg pots look attractive. Sensor electronics mass is not considered in this estimate; the difference would be exaggerated further if it were. The resolver mass would likely have been even higher, if rotary transformers were included in the package to preserve its clean signal. Furthermore, existing resolver-to-digital (R/D) electronics were not available with class S radiation-hardened parts. The most promising specification indicated a 20-krad demonstrated capability with local shielding, so a qualification test program would have had to be undertaken. 1 he estimated cost for this effort was $450,000, and success was not assured. Pots, seductively priced at 17% of their competition, appeared to be a reasonable choice.

The primary focus of the trade study was to contrast the cost and likelihood of success of qualifying the 16-bit resolver electronics on the one hand, against the accuracy and vacuum reliability of pots on the other hand. The risks of using a resolver were investigated more thoroughly than those of the pot. In fact, we assumed that the pots would not require a development effort. We surveyed resolver vendors for quality and drafted a qualification plan for the R/D converter. Little scrutiny was applied to components' ability to survive the temperature and vibration environments. Because accuracy requirements were relaxed just enough to allow the pot to be competitive, reliability and overall mass became the determining qualities of merit.

The study team investigated reports of poor pot reliability in a literature search.[1] Their findings warned that electrical noise could occur in pressures below 1 E-5 Torr, particularly if the sliding electrical contacts were not lubricated. 1 here were also reports of failed internal mechanical switches used to alternate between pot elements and avoid the deadband of each element. This concern was obviated, however, because our switching would be done by digital electronics inverting the most significant bit of one pot element in a pair.[2] The technique of switching between these elements, designated "primary" and "secondary", is illustrated in figure 3. Wear did not appear to be a significant problem for this application; our requirement for total revolutions was about 1/1 O to 1/20 of the value where electrical noise was observed to commence in life tests of other pots.

We had set successful spaceflight heritage as an important criterion for sensor selection. This was not a problem for the resolver, but our choice of pots was limited to those offered by only one pot vendor who could demonstrate the capability to manufacture a multi-element pot with the required accuracy. A large outside diameter of 3 inches would be necessary to achieve the linearity requirement. Although it was believed that this particular design was sufficiently similar to other flight-qualified units, we failed to thoroughly research the heritage of these pots. When failures in test occurred, it was determined that this design had not actually been used in a spaceflight or vacuum application. The pot vendor had built similar, although smaller, pots for spaceflight use; unfortunately, important design differences and unfavorable scaling of their response to a dynamic environment rendered those units inapplicable to qualify the large pots by similarity.

Under pressure to choose in a constrained-cost environment, the team committed to using pots,

SPECIFICATION

A general cross section view of the pot is shown in figure 4. The resistive and conductive tracks are two annular rings on each element, co-molded into the Diallyl Phthalate (DAP) disk substrate during fabrication. Each pot element is manually trimmed to specified linearity by grinding away small fractions of these co-molded resistive tracks by removing material from an annular channel that is cut adjacent to the track for this purpose. A thin electrical wiper contact, whose contact force is controlled to approximately 15 cN, sweeps over each track. As seen in figure 5, two wipers per element, originally made of Beryllium Copper alloy, are resistance welded to their wiper arm. The wiper arm grips an insulating ring on its respective hub by friction generated through spring force when the arm is sprung open, much like a retaining ring, to install it on the hub.

As is common with aerospace procurements, there was schedule pressure to release a specification for the potentiometer Request For Proposal at the earliest possible time, because of the lengthy procurement lead time. This left some important areas incompletely or inadequately defined. This discussion details aspects of the specification that received insufficient attention or suffered from lack of mature analysis at the time of contract start.

The specification was written at least 6 months before a preliminary structural analysis of the SAD design was completed. Without conservative interpretation of a preliminary analysis, the designer was forced to guess at the vibration levels that the pot may experience at its mounting surface. The value chosen was 19.6 grins, or 1.24 times the level of 15.7 grms input to the SAD mounting points during protoflight test. Also, while the specification called for a safety factor of 2.0 yield and 3.0 ultimate throughout the pot design, no analysis was done to verify these margins. We relied entirely on the pot vendor's past experience in similar dynamic environments.

Some features of the '(inherited" units departed from well-known, good design practice. While any change from inheritance should be considered with great caution, some design changes are appropriate risks. For example, the hub of each pot element was fastened to the common shaft by one cone point set screw in the proposed design, This shortcoming was noted at the pot's design review, but a non-standard solution was effected: the single fastener interface to the shaft was retained, but that fastener was backed up by another set screw to lock it in.

Absolute linearity was defined and limited to within ±0.1% for each element per Variable Resistive Components Institute Industry Standard VRCI-P-100A[3].

1 hereafter, the four elements had to be aligned so that the signal from either of the two redundant element pairs would deviate less than ±0.115% from absolute over a full revolution.

The initial release of the specification required that units assembly take place in FED-STD-209 class 10,000 or better conditions. We later found that, in practice, this was difficult or impossible to achieve with the limited clean room equipment available to the pot vendor. To preclude contamination in shipping, a packaging method which seals the pots into individual nylon bags was called for.

FAILURE, INVESTIGATION, AND REDESIGN

Problems began to surface prior to manufacturing the units. JPL's Quality Assurance representatives surveyed the manufacturer's facility and found its cleanliness and process controls to be typical of most commercial houses, i.e., inadequate. However, the pot vendor did correct these discrepancies, as verified by a follow-up QA report.

Packaging

The first lot of units was received with incorrect packaging. They were externally contaminated with fibrous debris from the packing material, the vent filter screens were held loosely by their retaining rings, and shaft torque measurements displayed noticeable torque variations over a full revolution. We convened a Material Review Board to disposition these concerns. The pot vendor explained that the torque variations are normal for this type of pot, with multiple elements and friction sources. The Board decided to use the pots as is, with the belief that any access path of a particle to the resistive elements within was sufficiently serpentine to preclude harm to those sensitive areas. The serial numbers of these first units were 001 through 004.

Loosened Hubs

Further problems with this first lot surfaced when protoflight tests began on the assembled mechanism. Random vibration tests developed calibration shifts of up to 40 mrad in the pots. We traced this phenomenon to internal looseness of the wiper hubs on the shaft, caused by failure of the set screw joint which, as mentioned, was the subject of concern at the initial design review. We implemented a successful solution on all subsequent lots: each steel hub was first mechanically fastened to the shaft with two set screw joints (one cone point, one cup point) at 90° to each other, then bonded with a bead of epoxy at the shaft/hub interface. The set screws themselves were blocked from backing out by a drop of epoxy. Absolute position error was measured by automated sampling of thousands of data points in a revolution. Subsequent vibration testing proved that these design changes successfully kept the pot elements within calibration.

Electrical Signal Noise

Electrical signal noise was experienced on many occasions. The noise most often occurred after vibration tests, but would sometimes be manifest before exposure to any flight environment. It was often of a very dramatic nature, sometimes opening the pot circuit altogether. A sample chart record of pot noise is shown in figure 6. The noise signature could vary considerably for each pot over extended running, from occasional blips to gross open circuits.

The effect that the noise would have on the SAD controller was not known. To justify expending the effort to correct this problem, controller behavior in response to typical pot noise had to be quantified. An electronic noise source was designed to inject varying voltages and pulse durations into the pot signal line. Two kinds of noise were generated: single-pulse and multiple-pulse. The single pulses were set at 200 ms, 400 ms, and 1 see, and from 1.0 to 3.5 volts amplitude. Multiple pulses were timed at 1 Hz and 2.44 Hz intervals, 2 Volts in amplitude, and pulse-width set at either 35 or 200 ms. These tests demonstrated that the controller was indeed sensitive to noise that approximated what we saw in pot testing, and that we needed to pursue efforts to eliminate the problem.[4]

For each of the first three lots, at least one representative unit was completely disassembled and subjected to failure analysis with the hope of finding a solution to pot noise and the other problems. This was a troublesome process, because the pot was designed such that epoxy bonds had to be chiseled loose, which generated debris. This debris interfered with the investigator's search for particulate contamination, sometimes yielding ambiguous results.

The failure analysis comprised the following minimum set of activities:

- Radiographic (X-ray) inspection of the units before disassembly
- Scanning Electron Microscope (SEM) visual and chemical analysis of internal surfaces
- Wiper force measurements
- Macroscopic video records of the pot elements as they were exposed, one by one, in disassembly

Serial numbers 001 and 004 from the first lot displayed a high degree of internal contamination, both metallic and fibers of DAP. The investigator judged that most of these did indeed result from the assembly and final calibration trimming process, Several particles were found clinging to the wipers, SEM photos of the wiper contacts showed some wear, even through the gold plating on some surfaces. Some of the tracks, both resistive and conductive, displayed discrete markings where their respective wiper was known to have rested during vibration. A SEM photo of atypical vibration mark is shown in figure 7. We concluded that the electrical noise was due to loose particles interfering with the electrical contact, and vibration damage to the contact surface. Although the contact's gold plating wore through in places, this probably was not a contributing factor, because noise also occurred before significant wear was experienced.

It is a common practice to apply lubricant to electrical contact surfaces. In an effort to smooth out resistance at the contacts and minimize surface damage during vibration, we built the next lot of pots, numbers 005 through 007, to the same specification, except that Bray 815 Z oil was applied to each track during assembly. We chose 815 Z oil for its compatibility with the same oil in the pot bearings. The pot vendor was cautioned to use the class 100 laminar flow bench more effectively for assembly operations.

We were rewarded with severe noise starting less than two revolutions into a run-in test of No. 006 pot in < 1 E-3 vacuum. Numbers 005 and 007 also displayed similar noise signatures, even before exposure to vibration.

Number 006 pot was dismantled and analyzed. The oil on most tracks had beaded into a dew-like appearance, and was clearly mixed with varying amounts of wear debris and other particles. DAP and cotton fibers were trapped on the wetted surfaces. A long cotton fiber was found intertwined in the noisy element No. 1 wiper, among a number of DAP particles in a matrix of black, tarry oil. A photo of one wiper, encrusted with these particles, is shown in figure 8. Although the tarry mixture contained conductive carbon wear debris, resistance measurements of the substance indicated $> 20\,M\Omega$ with micrometer probes. Concerns were raised about traces of epoxy found to have outgassed onto internal metal surfaces, and of a varnish with volatile constituents used to seal the calibration trim groove. Nevertheless, no trace of either material could be found on the element tracks or wipers.

Our findings, and the pot vendor's opinion, convinced us that the contact lubricant was not helpful, and could actually be trapping debris and exacerbating the noise problem. In fact, most of the wiper contacts displayed more wear in SEM photos, as shown in figure 9, than did the unlubricated contacts with the same normal force.

It was also clear that much stricter cleanliness measures had to be taken. However, our failure analysis of specific elements showed only a fair correlation between particulate contamination and electrical noise. To vanquish the noise, both the pot vendor and the mechanism design engineers agreed that it would be beneficial to increase the wiper contact force. The first two lots were built with the pot vendor's standard 10 to 11 CN contact force specification; this low force was desirable to minimize friction torque. Any increase in torque would proportionately increase the error of the SAD's rotational axis signal due to the torsional wind-up of the pot drive coupling. The risk was assessed, and it was agreed that the contact force could be increased to 18 ± 4 cN. This was accomplished by re-forming the Be-Cu alloy wipers to increase their preload when assembled to the same geometry as the previous pots.

Wiper Contact Fracture

The new lot of pots, numbers 008-012, entered vibration test with acceptable characteristics. Unfortunately, we found that the wipers had not been adequately re-engineered; the wipers fractured halfway through the random vibration test at regions of high stress. The fracture was observed as the pot signal was monitored in vibration; a sudden step change in the position signal occurred as a new contact point was established with the stub of the remaining wiper.

Metallurgical analysis of the failed wipers showed they had broken due to crack propagation from fatigue loading, followed by ductile failure. Failure analysis photos of a representative broken wiper are shown in figures 10 and 11. It turned out that Be-Cu alloy No. 25, in the half hard condition and fully heat treated after forming, was among the least fatigue-resistant of Be-Cu alloys.

We turned to the J. M. Ney Company, a firm that specializes in the design, test, and manufacture of sliding electrical contacts, for a solution. Ney recommended its Paliney-7, a precious metal alloy primarily comprising palladium, silver, gold, copper, and platinum. This material was developed for use in sliding electrical contacts, and has been applied in other manufacturers' pot designs. The available fatigue property data for this alloy suggested that it would be fair to expect excellent performance in vibration. New wiper contacts of Paliney-7 were fabricated to a contact force specification of 20 $\pm$ 4 cN, and assembled into the final lot, serial numbers 013 through 018.

The Engineering Model SAD was used as an instrumented test-bed to determine the actual dynamic environment at the pot. We found accelerations of up to twice the specified 19.6 grins pot capability. To mitigate the structure's amplification, the vibration spectrum input to the SAD was notched.

This fourth design lot successfully passed all screening and qualification tests. We employed advanced, real-time x-ray technology to perform Non-Destructive Evaluation (NDE) of pot internal parts after they were subjected to the qualification tests. This approach yielded objective, convincing evidence of unit integrity when optical inspection was impossible.

We proceeded to perform a life test to verify that the performance did not degrade within the 30,000 revolution requirements Because the SAD often operates in an oscillating mode, a motion controller was designed to emulate flight-like operation with a substantial number of oscillating cycles. The total number of test cycles was 188,907. These comprised approximately 30% continuous rotation and 70°/0 oscillating mode. Prior to the life test, the subject pot was vibrated at three specific shaft positions, with different levels of random input at each level. Temperatures of 24°, 40°, and 75° C were applied in a bell jar evacuated to < 5 E-5 Torr. The rate was generally accelerated 60x the flight rate to achieve enough wear in the limited time available. The test was periodically stopped to check for pot calibration shifts and friction torque. Signal voltage was continuously monitored; we observed wiper contact behavior by recording, alternately, the actual contact resistance or rapidly changing anomalies in the signal voltage.

Results from life testing were favorable. Element number three tended to have more noise than the others, but within acceptable bounds. By comparing the noise amplitude and location with the vibration level at that shaft dwell position, a clear correlation between vibration damage (figure 9) and noise was observed. Noise behavior at rates ranging from lx to 120x flight showed no significant rate dependence. A trend towards increased shaft friction torque was noted; average values at the start of the test were 0.0105 Nm, increasing to 0,0199 Nm at the end. Average error remained within specification for the duration of the test, although a worsening trend is clear (figure 12).

Table 3
Potentiometer Design History

	Potentiometer Serial Number			
	001–004	005–007	008–012	013–018
Wiper Track Lubricant	None	Bray 815 Z	None	None
Wiper Force	10 to 11 cN	10 to 11 cN	18 ± 4 cN	20 ± 4 cN
Wiper Material	Be-Cu	Be-Cu	Be-Cu	Paliney 7
Hub Fastening	Single set screw joint	Two set screw joints + hub bond	Two set screw joints + hub bond	Two set screw joints + hub bond

LESSONS LEARNED

1) Seek out and consult with established industry experts when persistent problems arise; don't try to save money and time with repeated efforts within your own organization.

The final design embodiment includes changes in wiper contact material, contact force, process and cleanliness controls, and improved fastening of internal parts. Of these, we attribute the critical enabling technology to the J. M. Ney Company, which advised on wiper material selection. Any engineer who is embarking on a design and development effort for a new electrical contact application would be well advised to consult with this company, and refer to its excellent textbook on the topic.[6] We also recommend the use of real-time radiographic services as a fast, cost-effective tool for NDE.[7]

2) There can be a high risk in buying custom-designed components which are based on qualification by similarity. If a good match of flight pedigree to requirements is not possible, a careful design analysis and/or early component qualification program should be planned. The use of engineering models is strongly recommended.

We developed screening and qualification tests which provided rapid, clear indication of pot flightworthiness. The engineering model SAD was an invaluable test-bed for instrumented vibration tests and early performance measurements.

The risks associated with the original SAD design using the resolver were investigated more extensively, including a QA survey of the vendor and a qualification plan for the Resolver-to-Digital converter. The probable cost of development for a resolver was estimated, As part of the apparent cost savings for the pots, it was assumed that development would not be required. It is wise to fully understand the qualification and the flight history of the custom component progenitors.

4) It is not always practical to develop a complete flow-down of requirements for components at the time that they need to be specified and procured. Under these circumstances, the specifications developed for the components must drive assembly design.

Sufficient analyses or special tests need to be performed to make the assembly design and performance compatible with the component specifications.

5) There is a real benefit in having QA residents at contractor facilities.

We may have avoided certain quality problems this way, or at least, could have made earlier decisions to disposition the questionable parts and avoid delays.

6) When faced with a development program, build and test as many solutions, in one iteration, as can be reasonably foreseen .

When problems do occur, pause long enough to plot out a course of action, Brainstorm all the possible fixes to the problem, and implement as many as possible at an early date. The added cost of building many design variations at once may be dwarfed by the cost of maintaining an organization through several cycles of redesign and retest. For example, the second lot of pots could have been built with the four permutations of high and low wiper force, coupled with lubricated and non-lubricated contacts.

7) Design assemblies for ease of disassembly as well as assembly.

The pace of failure analysis was slowed due to the great caution required to disassemble the pots. Moreover, confidence in the meaning of the analyst's findings was diminished. Redesign and rebuild cycles could have been faster if new flight pots did not have to be fabricated from scratch at each design iteration.

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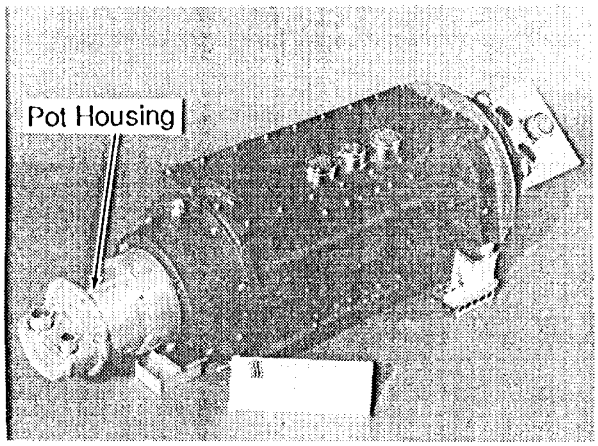
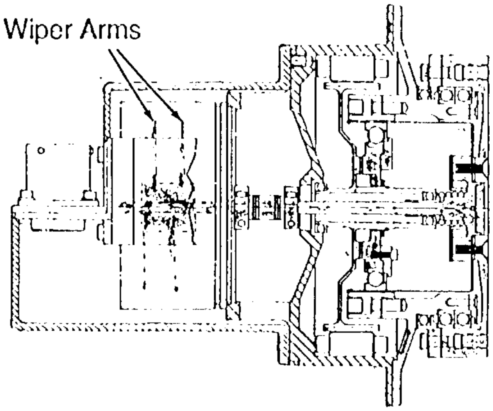


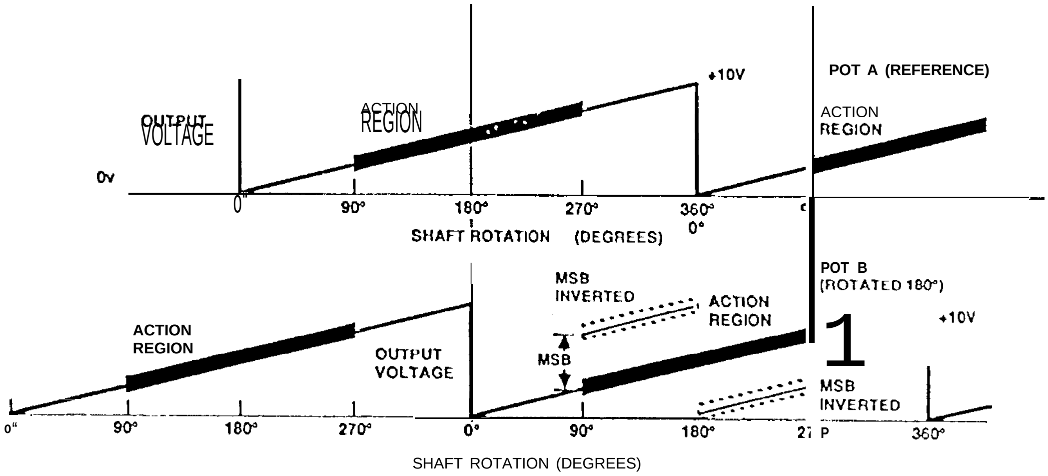
TOPEX/POSEIDON SAD

Figure 1



Potentiometer/Actuator Module

Figure 2



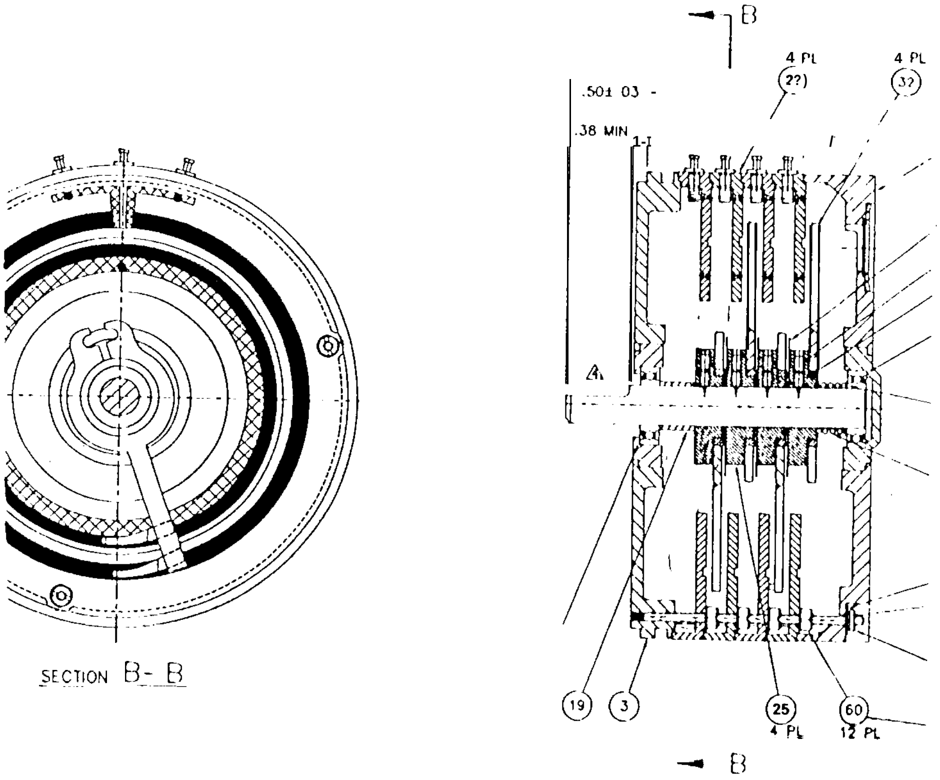
ALGORITHM

(1) WHEN IN ACTIVE AREA OF POT A. USE DIGITIZED OUTPUT UNMODIFIED

(2) WHEN IN ACTIVE AREA OF POT B, INVERT MSB OF DIGITIZED OUTPUT

Digital Method of Selecting Active Potentiometer Element

Figure 3



Potentiometer Cross Sections

Figure 4

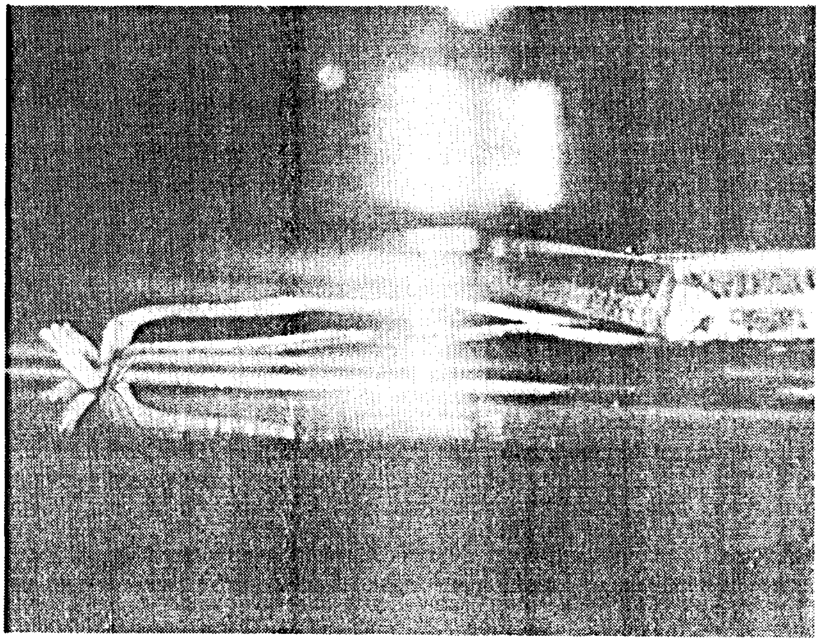


Photo of Typical Wiper Contact Pair

Figure 5

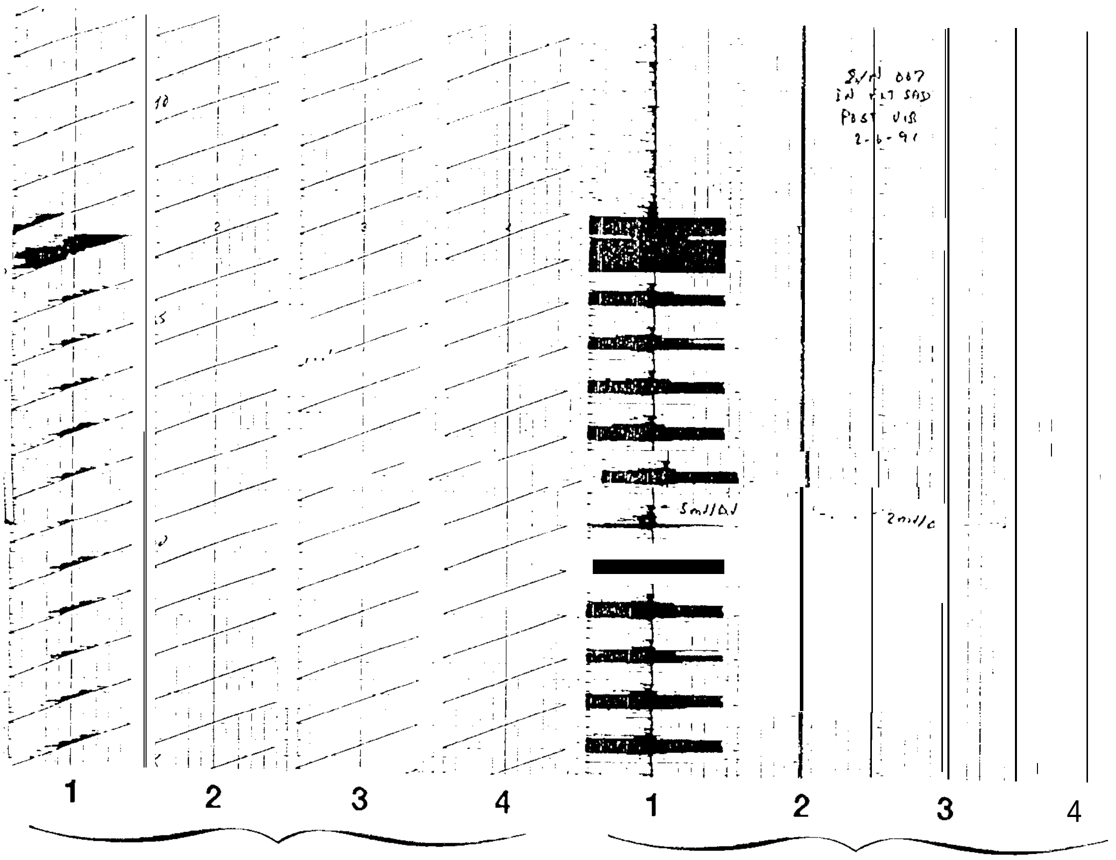
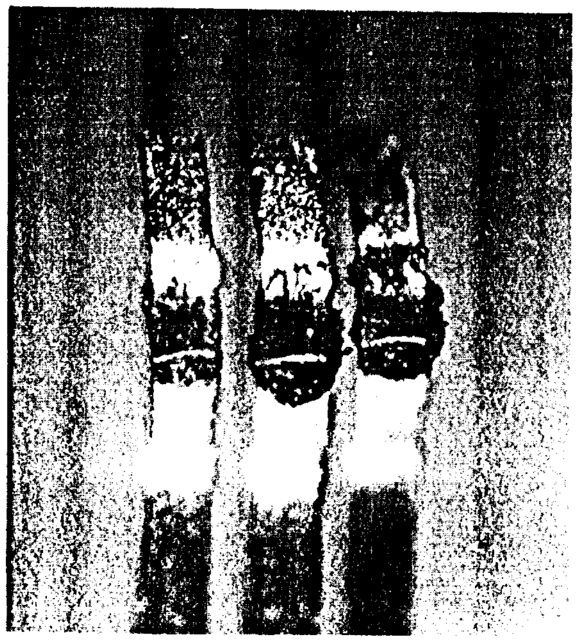


Chart Record of Noise on **Pot SN** 007 **after Vibration, Elements 1 through 4.**

Figure 6

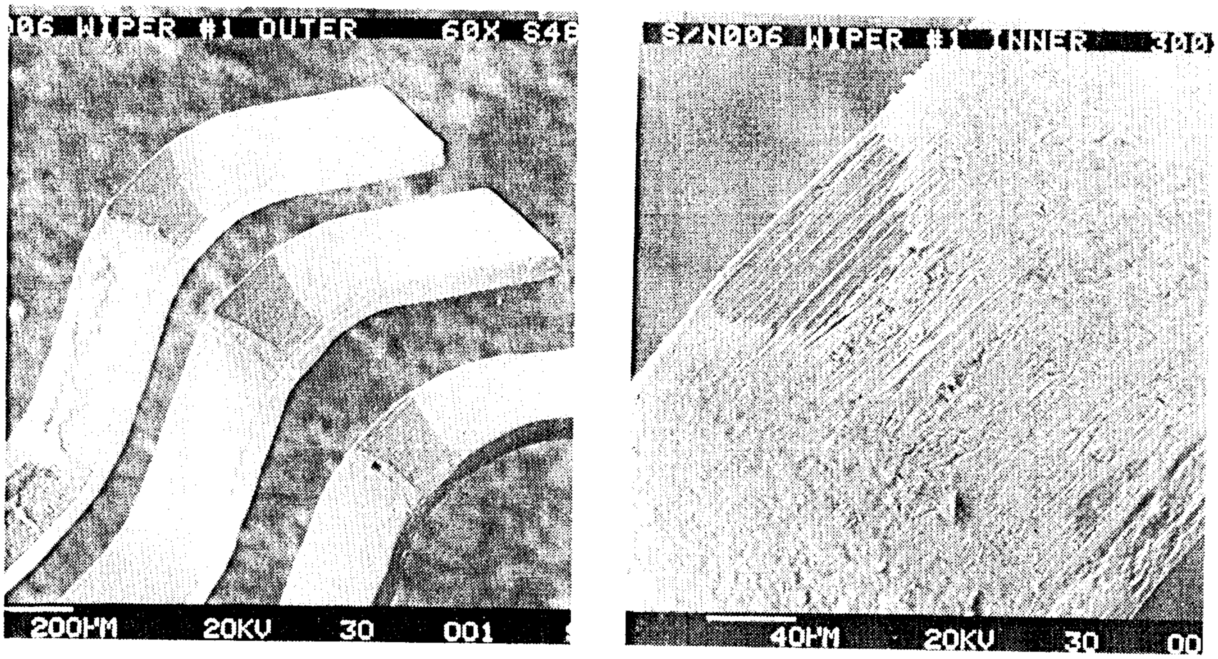
Element Damage from Vibration at Wiper Contact Dwell Point

Figure 7



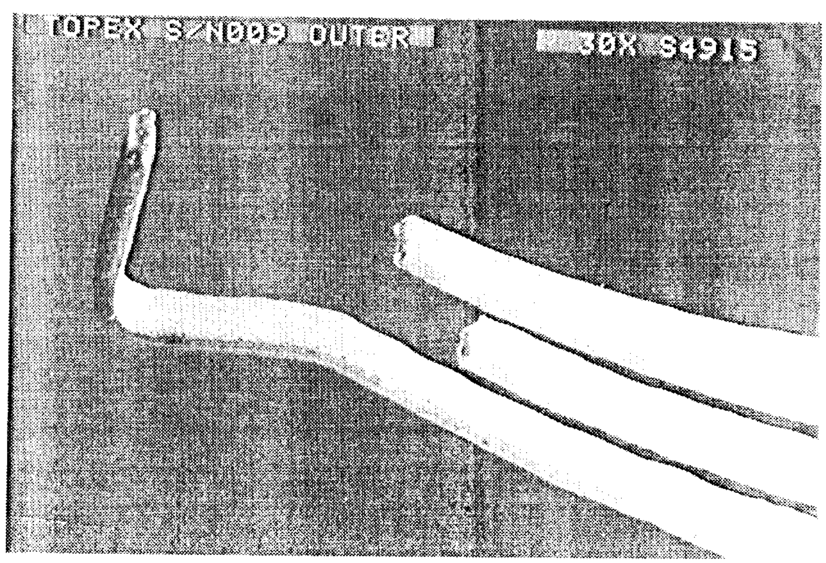
Oil and Wear Debris Slurry on SN 006 Wiper Contacts

Figure 8



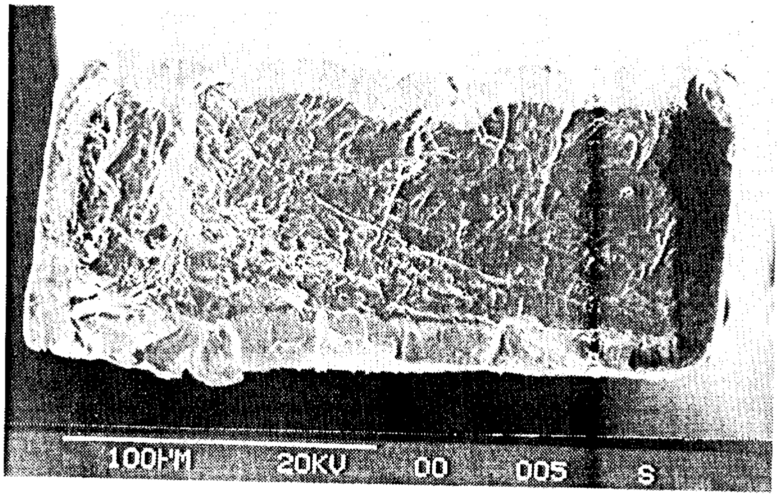
SEM Photo of SN 006 Wiper Contact Wear

Figure 9



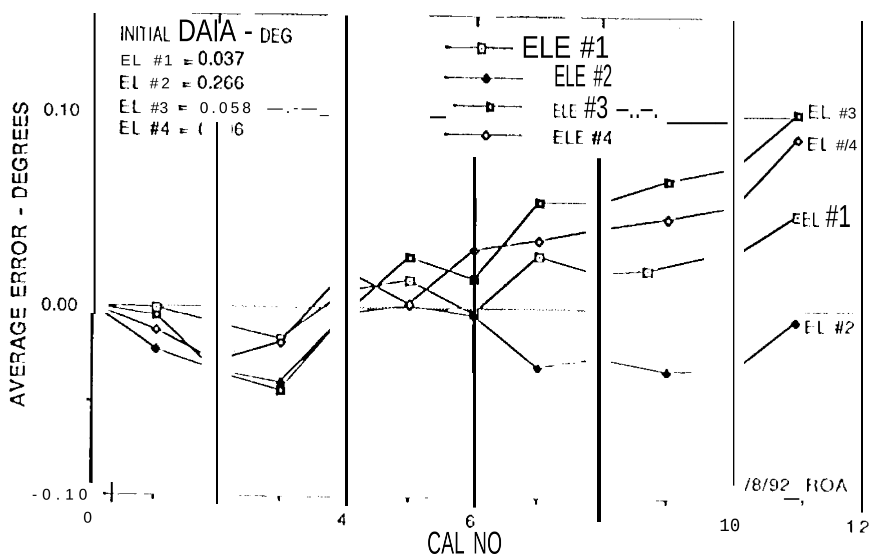
SEM Photo of SN 009 Fractured Wiper

Figure 10



SEM Photo of Fracture Plane, Showing Gold Plated Outer Layer

Figure 11



Life Test Calibration Trend for SN 016 Pot Elements

Figure 12